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What is the net PV energy production in Switzerland and how can we maximize it?

What is the net PV energy production in Switzerland and how can we maximize it?

P. Martinez-Alcaraz[1], G. Serra-Coch[1], C. Alonso-Montolio[2*], H. Coch[2]

[1] Laboratory for Human Environment Relations in Urban Systems (HERUS), École Polytechnique Fédérale de Lausanne (EPFL), Switzerland.

[2] Architecture, Energy & Environment (AiE), Polytechnic University of Catalonia (UPC), Barcelona, Spain.

* Corresponding author carlos.alonso-montolio@upc.edu

Abstract. Maximizing solar energy production in Switzerland is key to meet energy transition goals. Understanding in detail the current situation, and the potential for expansion is important to develop effective strategies. With this study, we want to contribute to federal and academic efforts to measure solar energy by estimating the net energy produced by photovoltaic (PV) installations when considering their embodied energy. We calculated the values of all energy produced by PV installations across Switzerland from 1991-2021 and subtracted the embodied energy used to manufacture the PV panels and their mounting system. We considered four different types: freestanding, attached-complex, attached-simple and integrated, with progressively decreasing values of embodied energy for the supporting structure. The results show that in 2022, 50% of PV installations were producing net energy, which accounts for an accumulated historical value of 1.000 GWh, implying that 6% of the historical PV generation is net energy. If mounting systems were minimized, the accumulated net energy would reach 23%, showing the importance of integrating PV panels in building elements. These findings suggest that policies to support the diffusion of photovoltaic panels should also ensure long term use of existing installations and consider the mounting systems' embodied energy for new ones.

1. Introduction

Expanding photovoltaic energy production is a relevant factor to support the global energy transition to a low-carbon energy system [1]. The Swiss government, within the Energy Strategy 2050, has adopted policy goals that include the phasing out of nuclear plants, the promotion of energy efficiency measures, and expansion of renewable energy production [2]. An increase in decentralized photovoltaic prosumers in the existing and future built environment is key to support this last objective. In order to maximize the solar energy production in Switzerland, it is important to understand in detail the current situation and the potential for expansion.

Recent efforts by private and public entities, as well as the academic community, have highly contributed to a better measurement of the solar energy production [2] and the existent solar potential in the built environment [3]. With this study, we want to contribute to these efforts by adding another dimension to the energy production measurements: the net energy produced by photovoltaic installations in Switzerland, calculated considering the embodied energy of the installations as well as the characteristics of the complete structure necessary for the installation.

2. Data and Methods

To calculate the overall net-energy produced in Switzerland by PV installations, we obtained the values of the total energy produced and subtracted the embodied energy used to manufacture the PV panels and their mounting system. We considered different types of installations depending on the mounting system. Installations on the ground (freestanding) or located over a building element (attached), were given higher values of the materials for the supporting structure than integrated ones.

2.1. Data collection

For this study, we combined three different datasets as well as multiple literature references. Firstly, we leveraged the effort of the Swiss Federal office of Energy (SFOE) to compile and publish all electricity production plants, including PV, registered in the Swiss system for guarantees of origin operated by Pronovo AG. This dataset includes the geographic location of the installation, the beginning of operation date, the total power installed and the type of installation (integrated, attached or freestanding) [4]. In addition, the SFOE has been calculating data on the electricity generated by PV installations per year since 1984 [5]. We focus on the period 1991-2021, when we have data in both datasets. Finally, we also used the solar potential of Soonendach.ch developed for SFOE [6], which contains buildings geometries and solar potential per rooftop in Switzerland.

2.2. Embodied energy PV installations

To calculate the embodied energy of PV installations, first we estimated the one of PV modules based on literature and then we added the one of the mounting system depending on the type of installation.

2.2.1. PV modules. Primary embodied energy value of photovoltaic modules is a challenging data to determine. Despite significant advancements in technology in recent years, most installed PV panels still use monocrystalline or polycrystalline silicon cells. These two types of technology still hold a market share of around 90% [7]. Their most significant energy consumption cost is associated with the process of silicon purification [8,9]. The embodied energy values of PV modules, whether monocrystalline or polycrystalline, vary greatly in the existing literature (Table 1), meaning that we should always handle them with caution [10]. The share of recycled material used can greatly explain the differences [11]. In this work, we are assuming recycled PV panels and we take an embodied energy value of 796 kWh/m^2 for monocrystalline silicon modules and 592 kWh/m^2 for polycrystalline silicon modules, aligned with the results of Koppelaar's meta-assessment of energy payback time [12]. We used annual data [7] to compute the share of monocrystalline and polycrystalline.

Table 1. Primary energy consumption for photovoltaics.

Author	PV modules technology	Embodied Energy[a] (kWh/m^2)	Source
Nawaz et al.	mono-Si	1710-1380	[9]
Kato et al.	mono-Si	1156-4311	[13]
Yue	mono-Si	1083	[14]
Koppelaar[b]	**mono-Si**	**796**	[12]
Alsema and Nieuwlaar	poly-Si	1278	[8]
Stoppato	poly-Si	639	[15]
Sumper et al.	poly-Si	773.2	[16]
Koppelaar[b]	**poly-Si**	**591.5**	[12]

[a] Values of embodied energy originally in different measure units have been converted to kWh/m^2.
[b] Originally pay-back in years and here harmonized to energy using Swiss irradiation values.

2.2.2. Mounting system. The balance of system components (BOS) includes the mounting system and the power-conditioning equipment [16]. The embodied energy of the latter is usually not considered [12] so we are only considering the mounting system. The embodied energy of the mounting system depends on the installation type: *Freestanding*, *attached-complex*, *attached-simple* and *integrated*, with a decreasing amount of material used and, thus, embodied energy. *Freestanding installations* (0.5% in Switzerland) are those directly positioned on the ground, without any type of attachment to a building element. Attached installations (81.1%) have been divided into complex and simple. *Attached-complex* are those installations on flat rooftops, with a mounting system that allow the panel to be tilted. *Attached-simple* are those on pitched roofs, with a simpler mounting system giving them the same tilt as the roof. *Integrated* (18.4%) installations are considered to be absorbed within the building elements, without a mounting system.

Firstly, we calculated the amount of material used in the different mounting systems.

(a) *Free-standing.* We considered a value of 322 kWh/m^2 [17].

(b) *Attached.* We distinguish between installations attached to flat or pitched roofs because the amount of material used in the first ones tends to be significantly higher to meet the desired tilts. As the PV panels dataset does not include this distinction, we used Geographic Information Systems (GIS) to identify these two types among the installations labeled as attached. We spatially matched the location of PV installations [4] with the nearest rooftop [6] (i) excluding 1.5% installations without location (ii) only selecting roofs with good, very good or excellent solar potential [18] (iii) comparing installed power of installation and available roof surface (considering 6 m^2/kWp, [6]) to validate the spatial match. 21% of the attached installations in the dataset were found to be on a rooftop with less than 8.5º tilt (15%, [19]) and considered as *attached -complex.*

(b1) *Attached-complex*. We took the mean value of 5.4 kg/m^2 of aluminum and 70 - 100 kg/m^2 for the concrete ballast. We obtained the aluminum value by benchmarking existing mounting solutions and consulting with experts in Europe [20]. The most common constructive system is built with aluminum profiles with weights from 2 – 12 kg/m^2 and concrete ballasts system for wind forces [21–24]. The ballast weight values were obtained from PV suppliers [25]. No benchmarking was conducted due to their low impact on the overall embodied energy of the mounting system.

(b2) *Attached-simple*. The structure tends to be mounted directly on the roof avoiding the use of ballasts. We considered 1 kg/m^2 of steel for the mounting and fixing system [26].

(c) *Integrated* . We disregard the value of the mounting system.

Secondly, we calculated the embodied energy per installation type using the specific embodied energy of each material. We considered 155 MJ/kg for aluminum, accounting for 33% being recycled with raw aluminum values at 218 MJ/kg and recycled at 29 MJ/kg [27]. We considered 1.39 MJ/kg for concrete [27] and 95 MJ/kg for steel [28]. Finally, we calculated the specific embodied energy per installation, mean value per installation type, and payback in years considering their specific solar radiation.

2.3. Net energy produced

To calculate the energy produced per PV plant per year, we divided the total energy produced per year [5] by the installed power of each PV plant [4]. We validated the result using a spatial dataset that contains data on solar potential per roof [6] and applying the GIS-based spatial matching method explained in section 2.2. Once we obtained the solar potential per PV plant based on their location, we used the methodology of Sonnendach-ch and SFOE [6] (to calculate the energy produced by installation, considering: Electricity yield (kWhe/year) = total radiation (kWh/m^2 year) * module efficiency (%) * performance ratio (%) * surface (m^2) * performance loss (%). We selected the calculated mean annual irradiation per square meter accounting for shading [6]. We considered 17% of module efficiency [6], 80% performance ratio [6], and a performance loss of 0.69% per year [29], considering that all PV installations are still functioning [6]. We used the power installed provided in the dataset for each installation to obtain their respective surface using a ratio of $6m^2$/1 kWp [6]. The validation was positive, with only a 6% difference in relation to the total energy produced estimation dataset for 1991-2021 [5].

Once we had both embodied energy and energy produced per type and year, we could obtain the break-even point, the percentage of clean energy up to date, the mean payback periods per installation type, and the number of installations producing clean energy once they arrived at their payback time.

2.4. Scenario
The last step was calculating a scenario where all (i) *attached-complex* installations were attached to the flat roof without a tilting structure minimizing the amount of aluminum used, assigning them embodied of the same mounting system as the *attached-simple* ones, (ii) all *attached-simple* become *integrated* to the pitched roofs, reducing the mounting and fixing systems to zero embodied energy while (iii) *integrated* and *freestanding* installations remained the same. To model this scenario, we re-calculated the energy produced using the alternative validation method explained in section 2.3, which considers the flat tilt angle of installations in flat rooftops. We also obtained for this scenario the break-even point, the % clean energy up to date, the mean payback periods per installation type, and the number of installations producing clean energy.

3. Results

3.1. Embodied energy
The mean value of the embodied energy for the PV modules is 689.5 kWh/m^2 (weighted average considering the number of installations per year and the share of mono and poly crystalline). Regarding the embodied energy for the mount systems, we obtained 256 kWh/m^2 for *attached-complex*, 26 kWh/m^2 for *attached-simple*, negligible for *integrated*, and 322 kWh/m^2 for *freestanding*. When computing the total embodied energy (module + mounting system) of the installation, *attached-complex* installations have 40% more than *integrated* and 10% more than *attached-simple*. *Freestanding* installations usually have values 4 times larger than the *integrated* ones, but this mounting system is rarely used in Switzerland. When we translate these results to payback time in years, *attached-complex* have 5.8, *attached-simple*: 4.1, *integrated*: 3.9, *freestanding*: 5.9.

In Switzerland, there are 64% PV installations *attached-simple* (49.7% of the total power installed), 18.4% *integrated* (12.5% of the total power installed), 17.1% *attached-complex* (37.2% of the total power installed), and 0.5% *freestanding* (6.7% of the total power installed). This means that, considering the proportion of different types, the total energy used to produce all PV installations in the country has values around 14.900 GWh.

When considering the scenario developed, where we aim at reducing the mounting system used, installations in flat rooftops are assigned the *attach-simple* system, installations in pitched roofs become *integrated* while *freestanding* ones remain the same due to the difficulty of integrating them in a building and their little overall impact. Thus, we have the following changes in the percentage of installations with each mounting system: *Attached-complex* (0%), *attached-simple* now becomes 17.1%, *integrated* become 82.4% and *free-standing* remain the same.

3.2. Net energy
The results show that at the beginning of 2022, 50% of PV installations in Switzerland are producing net energy, which accounts for an accumulated historical value from 1991 to 2021 of around 1.000 GWh. Thus, in 2022, 6% of the historical PV generation could be considered as net energy (Figure 1, Table 2).

In the case of the scenario, when minimizing the use of mounting systems and maximizing integration of PV panels in the building elements, the net energy produced from 1990-2021 would increase to an accumulated value of 3.900 GWh. Which means 23% of the total PV energy produced would be net energy, and 54% of PV installations in Switzerland would be producing net energy.

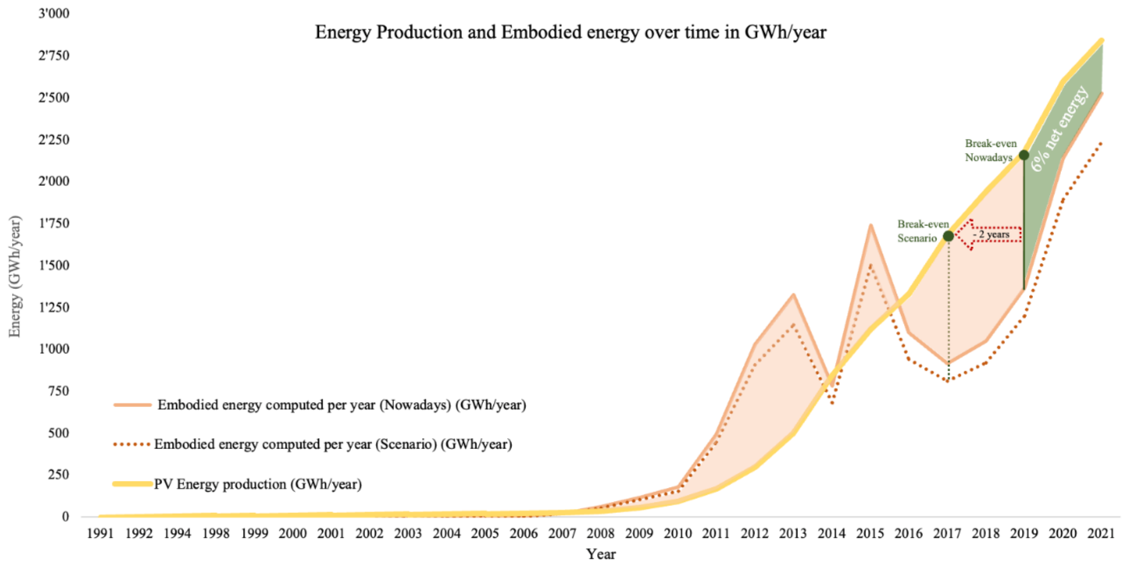

Figure 1. Energy production and embodied energy among time. The figure represents the difference of energy embodied vs generated; the break-even point is calculated with the accumulated values. The embodied energy is correlated with the number of PV installations entering on operation that year, which explains the maximum and minimums points of the curve. Source: Authors

Table 2. Results in 2022 and scenario minimizing mounting system.

	1990 - 2021	Scenario
Installations producing net energy (%)	50	54
Net energy produced (%)	6	23
Net energy produced (GWh)	1.000	3.900

4. Conclusion

These results point out to the existence of currently hidden energy costs that should be accounted for when evaluating the renewable energy performance of Switzerland. When considering these hidden costs, the national net energy production is lower than expected. The study also shows a difference between installation types in terms of embodied energy and its impact in energy payback time. This highlights the value of considering time as a key variable when accounting for energy management. The PV panels installed years ago are those producing net energy nowadays and, thus, the ones we are installing now will provide the energy of the future. Therefore, from an energy-cost point of view, solar energy is a long-term investment that will only provide the desired results if maintained with a long-term view and planning.

These findings suggest that policy measures to support the diffusion of photovoltaic panels, aside from increasing the overall number, should also focus on (i) monitoring existing ones and ensuring their long lifetime and (ii) considering the installation type and choice of materials with low embodied energy for new installations. In order to foster these two approaches, (1) technical and financial aid could be provided to support appropriate maintenance and long lifetime of existing installations, (2) existing installations could be regularly monitored to ensure their maximum efficiency conditions as well as their preservation in time (3) integrated and low embody energy installations could benefit from additional aid in order to facilitate their diffusion among the Swiss society.

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